MOLECULAR CLOUDS AND THE LARGE-SCALE STRUCTURE OF THE GALAXY

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ABSTRACT

We review the application of molecular radio astronomy to the study of the large-scale structure of the Galaxy and describe the distribution and characteristic properties of the Galactic population of Giant Molecular Clouds (GMCs), derived primarily from analysis of the Columbia CO survey, and its relation to tracers of Population I and major spiral features. The properties of the local molecular interstellar gas are summarized. The CO observing programs currently underway with the Center for Astrophysics 1.2 m radio telescope are described, with an emphasis on projects relevant to future comparison with high-energy γ-ray observations. Several areas are discussed in which high-energy γ-ray observations by the EGRET experiment aboard the Gamma Ray Observatory will directly complement radio studies of the Milky Way, with the prospect of significant progress on fundamental issues related to the structure and content of the Galaxy.

I. HISTORICAL PERSPECTIVE

Since the pioneering work of Shapley and others led to the recognition that the Milky Way is a spiral galaxy, its large-scale structure has been the subject of much investigation. The classical optical studies toward the more distant portions of the Galactic disk made in the early decades of this century were typically confined to a few, well-defined "windows," owing to the severe obscuration in visible light from interstellar gas and dust. With the advent of radio astronomy, following the pioneering efforts of Jansky and Reber, and, in particular, the discovery by Ewen and Purcell in 1951 of the 21 cm hyperfine transition of atomic hydrogen, astronomers could begin to assemble an accurate picture on a Galactic scale of the distribution of matter in the Milky Way. Today, the discipline of Galactic radio astronomy is crucial to the continuing study of our Galaxy and its main constituents.

Within a few years of the discovery of the 21 cm line of atomic hydrogen (H I), the Leiden survey of the northern sky (Muller and Westerhout 1957) and the Sydney survey of the southern sky (Kerr, Hindman, and Gum 1959), done with inexpensive, moderate-size antennas largely dedicated to hydrogen-line work, had completely mapped at ~2° resolution the distant spiral arms around the Galactic equator and followed the local gas to sufficiently high latitudes (±10°) to establish a secure foundation for subsequent studies at higher resolutions. Progress has neither been as rapid nor as systematic in the study of the molecular component of the interstellar medium (ISM).

a) Molecular Radio Astronomy

Until the 1960s, astronomers generally believed that molecules are extremely rare in interstellar space. Nearly all visible matter (99% in terms of number of atoms) in the cosmos is hydrogen and helium. Helium, an inert gas, does not form molecules, and, although hydrogen atoms combine to form H_2, the bond is easily broken by the ultraviolet radiation emitted by luminous stars that pervades the interstellar medium. More complicated molecular species were thought even less likely, given the conceptions then current of gas-phase chemistry at the low densities characteristic of the ISM.

During the last three decades observations of molecules in interstellar space have demonstrated dramatically the fallacy of those early assumptions. Rapid advances in microwave spectroscopy following the Second World War enabled accurate laboratory measurement of the frequencies of key molecular transitions and led to the radio detection of interstellar molecules, starting with OH (Weinreb *et al.* 1963), followed by water vapor and

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ammonia (Cheung *et al.* 1968, 1969) and formaldehyde (Palmer *et al.* 1969). An accelerating pace of discovery continues to the present day. To date, nearly 100 interstellar molecules have been detected and identified, ranging from simple diatomics to fairly complex organic structures with molecular weights as large as 147 (see, for example, Winnewisser and Herbst 1987). Molecules exist primarily in the depths of dark nebulae and in dusty circumstellar shells, where concentrations of interstellar gas and dust severely attenuate the ultraviolet radiation that would otherwise break molecular bonds. Star formation takes place within such dense molecular clouds. Multiwavelength studies of numerous molecular transitions provide information on the density and temperature structure of the interstellar molecular clouds that produce stars and on the interaction of both young and evolved stars with their environment through outflows and shocks as they contribute to the continuing dynamic evolution of the interstellar medium.

b) CO as a Tracer of Molecular Hydrogen

Of all the molecules detected so far, however, interstellar carbon monoxide (CO), discovered by Wilson *et al.* (1970), has probably had the greatest impact on astronomy in general. The second most abundant molecule in interstellar space after H_2, CO is a simple, stable diatomic very widely distributed throughout the Galaxy, and it is collisionally excited into detectable emission within clouds where the density exceeds ~100 molecules per cm^{-3}. Because the abundance ratio of CO to H_2 is relatively high for a trace constituent, about $1{:}10^5$ and apparently remains fairly constant over a wide range of interstellar conditions, CO has become the standard tracer of molecular hydrogen in the ISM. The $J{=}1{\rightarrow}0$ rotational transition of CO at 115 GHz, readily detected at millimeter wavelengths at 2.6 mm, is now the molecular analog of the 21 cm atomic hydrogen line for large-scale studies of interstellar gas in the Galaxy.

The first Galactic CO surveys were confined typically to a strip along the Galactic equator in the northern hemisphere where only a minute fraction of the molecular gas in the Galaxy was actually observed (Scoville and Solomon 1975; Gordon and Burton 1976; Cohen and Thaddeus 1977). Yet some of the most interesting scientific issues raised by the discovery of cosmic molecules, such as the structure and evolution of molecular clouds and their place in the Galactic hierarchy, require unbiased surveys covering large areas of the sky. More than 15 years ago, our group initiated the first large-scale survey of molecular emission intended to encompass the entire Galactic disk. Using an antenna with a modest 1.2 m aperture at Columbia University in New York City, now at the Center for Astrophysics in Cambridge, and a twin instrument located on Cerro Tololo in Chile, we have recently completed at least the first phase of what has turned out to be an extremely ambitious project, since molecular gas in the Galaxy is far more extensive than first supposed. The program has three main objectives: 1) to produce a fairly complete and unbiased inventory at low resolution of both nearby and distant molecular clouds for comparison with other large-scale Galactic surveys, especially the IRAS far-infrared survey at 100 μm and the COS-B survey of diffuse high-energy γ-rays; 2) to survey the distant molecular clouds in the inner Galaxy at full resolution to determine masses and characteristic properties; and 3) to study in detail individual nearby clouds, especially those associated with well-known regions of star formation.

II. THE COLUMBIA CO SURVEY

The culmination of our low-resolution CO work is a composite map at $0\overset{\circ}{.}5$ resolution of the molecular clouds in a thick band along the Milky Way, described in detail in Dame *et al.* 1987. Table 1 lists our surveys that contributed to the composite map with other major surveys undertaken with the northern and southern 1.2 m telescopes. All these observing projects have been conducted primarily of the main CO isotope at 115 GHz. The major scientific results of this large compendium of data can be summarized under the following headings (see Dame *et al.* 1987 and references in Table 1 for details).

TABLE 1
MAJOR CO SURVEYS UNDERTAKEN WITH THE 1.2 M TELESCOPES IN THE U.S. AND CHILE

SURVEY	REFERENCES
Molecular Clouds in Orion and Monoceros	Kutner et al. 1977; Maddalena et al. 1986
Cygnus X Region of the Galactic Plane	Cong 1977
Deep Survey of the First Galactic Quadrant	Cohen et al. 1980, 1986; Dame et al. 1986
Molecular Clouds in the Vicinity of W3, W4, and W5	Lada et al. 1978
GMCs Associated with the Rosette Nebula, NGC 2264, and CMa OB1	Blitz and Thaddeus 1980
Large Star-Free Cloud in Monoceros	Maddalena and Thaddeus 1985
Wide-Latitude Survey of the First Galactic Quadrant	Dame and Thaddeus 1985, Grenier et al. 1989
Supernova Remnants in the Outer Galaxy	Huang and Thaddeus 1985, 1986
The Carina Arm	Cohen et al. 1985; Grabelsky et al. 1988
Southern High-Latitude Clouds	Keto and Myers 1986
Dark Nebulae in Perseus, Taurus, and Auriga	Ungerechts and Thaddeus 1987
Entire Milky Way (composite survey)	Dame et al. 1987
Region of the Galactic Center	Bitran 1987
IR Cirrus in Ursa Major	de Vries, Heithausen, and Thaddeus 1987
Wide-Latitude Survey of the Third and Fourth Galactic Quadrants	May et al. 1988; Nyman 1990
Deep Survey of the Fourth Galactic Quadrant	Bronfman et al. 1988
Large Magellanic Cloud	Cohen et al. 1988
Small Magellanic Cloud	Rubio et al. 1989
Southern Coalsack	Nyman, Bronfman, and Thaddeus 1989
Thirty-Four Galactic Clusters	Leisawitz et al. 1989
Dark Clouds in Ophiuchus	de Geus et al. 1990
The Polaris Flare Near the North Celestial Pole	Heithausen and Thaddeus 1990

a) Giant Molecular Clouds

Approximately half the hydrogen gas in the Galaxy is in molecular form. The H_2 gas is more highly concentrated toward the inner Galaxy than the atomic hydrogen and most dense in a "molecular ring" between four and eight kpc in galactocentric radius. Its half-thickness with respect to distance above and below the plane, approximately 87 pc, in contrast to that of atomic H, is close to that of the Population I stars, underscoring the intimate relationship between molecular clouds and regions of star formation. Molecular gas is usually found in extensive complexes, called Giant Molecular Clouds (GMCs), which are clumpy in nature, exhibit power-law relations among size, mass, and velocity dispersion and appear to be in approximate virial equilibrium. The mass spectrum of these giant objects is fairly "flat," with most of the mass residing in the largest concentrations. On the basis of analyses of GMCs extending from the molecular ring at R~4 kpc to the Perseus Arm beyond the solar circle, the mass cutoff for giant molecular clouds at the high end is apparently between 5×10^6 and 10×10^6 $M_\odot$, with 50–70% of the total mass in objects more massive than 10^6 $M_\odot$. Bronfman et al. (1988) derived from a joint analysis of our northern and southern surveys a total molecular mass of 1.2×10^9 $M_\odot$ between R=2 kpc and the solar circle.

b) "Local" Molecular Clouds and Dark Nebulae

On the basis of our surveys, the bulk of the molecular gas within about 1 kpc of the Sun has been partitioned into discrete clouds, most of them associated with dark nebulae, opaque "rifts," stellar associations, and other tracers of Population I observed in optical studies of the nearby interstellar medium (Fig. 1). As had been suspected previously from the distribution of dark nebulae, molecular clouds near the Sun are much more common in the northern Milky Way than in the southern: the molecular mass within 1 kpc is 4 times greater in the first and second Galactic quadrants than in the third and fourth. Table 2 summarizes the physical parameters characterizing the local molecular gas. Although conspicuous nearby dark nebulae such as the Taurus and Ophiucus dark clouds and the Great Rift in Cygnus are modest in size and mass relative to the GMCs, owing to their proximity to the solar system they are of considerable interest because star formation, particularly that of late-type stars, can be studied there in great detail.

TABLE 2

MOLECULAR GAS WITHIN 1 KPC

rms z dispersion	74 pc
Layer thickness (HWHM)	87 pc
Mass	4.0×10^6 $M_\odot$
Surface density	1.3 $M_\odot$ pc^{-2}
Midplane density	0.0068 $M_\odot$ pc^{-3} 0.10 H_2 cm^{-3}
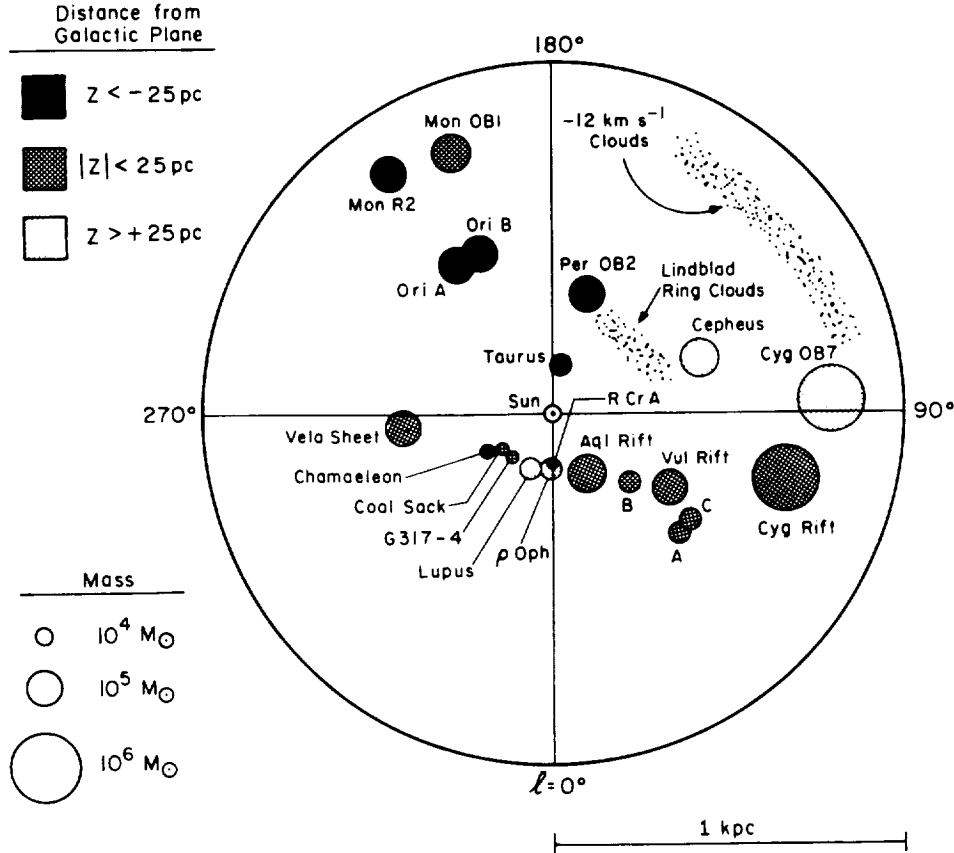
FIGURE 1. The distribution in the Galactic plane of molecular clouds within 1 kpc of the Sun (Dame *et al.* 1987). The diameters of the circles are proportional to cloud size; shading indicates distance from the Galactic plane.

c) Galactic Structure

From an intercomparison of our low-resolution CO survey, 21 cm atomic hydrogen surveys, and the Galactic diffuse high-energy γ-ray emission observed by COS-B, the important CO-to-H_2 conversion ratio, X (the ratio of velocity-integrated CO line emission, W_{CO}, to H_2 column density), required to derive the mass of molecular clouds, has been calibrated over much of the Galaxy. The result of this analysis (Strong *et al.* 1988), $N(H_2)/W_{CO} = 2.3\pm0.3 \times 10^{20}$ molecules cm^{-2} (K km s^{-1})$^{-1}$, is in good agreement with that derived under different, independent assumptions by two other methods, star counts and the virial theorem.

Our northern and southern surveys demonstrated that molecular clouds delineate prominent spiral features in the Galaxy. The Perseus and Carina arms in the outer Galaxy, for example, are particularly well defined in molecular clouds, and, in the local neighborhood,

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nearly all the clouds within 1 kpc in the first and fourth quadrants apparently lie on a fairly straight ridge more than 1 kpc long which may trace the inner edge of a Local spiral arm.

Although results for the inner Galaxy are much less satisfactory, owing to the well-known problem of the two-fold kinematic distance ambiguity for clouds within the solar circle, we and others have shown that the Sagittarius Arm in the first Galactic quadrant is fairly well defined by large clouds (Dame *et al.* 1986; Clemens *et al.* 1988; Solomon and Rivolo 1989) and that it may join the Carina Arm in the fourth quadrant to constitute a single feature at a pitch angle of about 10° extending nearly three-quarters of the way around the Galaxy (Grabelsky *et al.* 1988). No unambiguous model yet exists, however, for the distribution of the molecular clouds within the molecular ring about halfway to the Galactic center.

III. PRESENT AND FUTURE WORK

The surveys listed in Table 1 represent a fairly complete inventory of the molecular gas associated with Population I objects in the Galaxy, but nearly all of them could be profitably extended in both resolution and sensitivity. A number of projects, described below, currently underway at the Center for Astrophysics, represent a logical continuation of these early low-resolution surveys.

TABLE 3

CURRENT CO OBSERVING PROJECTS — CFA 1.2 M TELESCOPE

SURVEY	PRINCIPAL OBSERVER(S)
Cas A Region	H. Ungerechts, P. Umbanhowar
Cygnus X Region	H. O. Leung
Gem OB1/IC 443 Complex	J G. Stacy
A First Quadrant Survey of Molecular Clouds in the Outer Arm	S. Digel
Diffuse, High-Latitude Molecular Clouds in the Second Quadrant	A. Heithausen
M31, Andromeda Galaxy	E. Koper, T. M. Dame
Selected Regions at High Latitude (GRO Survey)	J. G. Stacy

a) Individual Regions

Our composite low-resolution CO survey is very useful for identifying regions of the Galaxy for high-resolution study. Table 3 lists major observing projects now being undertaken at the CfA with the 1.2 m telescope, nearly all them being carried out at full resolution (1/8°) and high sensitivity; in its present configuration with a superconducting SIS receiver, the CfA instrument is the most sensitive in the world ($T_{SSB} \sim 60$-70 K) at the CO frequency. Giant clouds associated with prominent star-forming regions dominate the list of current observing programs, particularly those, such as the Cas A and Gem OB1 complexes, which, although distant, are also visible optically, allowing detailed comparison of observations taken at many wavelengths. Among many general issues addressed by such studies are some of the most challenging in the fields of star formation, Galactic structure, and interstellar gas chemistry and dynamics: How do these huge concentrations of dense gas form, and how do they evolve? How long do they last? What is the efficiency of star formation? How does star formation depend on density and other parameters, and how destructive is it to the structure and integrity of the parent clouds? If star formation in the giant clouds represents a self-propagating conflagration, as some observations suggest, on what time scale does this process operate and what is the relative contribution to it of the two most likely sources of disruption, supernovae and winds from OB stars?

b) Isotopic and Multiple Transition Studies

The validity of CO as a mass tracer of molecular clouds is being continually tested. In general, the optical thickness of the CO 1→0 line implies that only a fraction of the CO gas in a particular cloud is being observed. For determining masses, CO line saturation appears not to be a serious problem, due to the clumpiness of the gas within a molecular cloud, apparently extending down to the smallest scales observable. Yet observation of more optically thin isotopic species, such as ^{13}CO and $C^{18}O$, are highly desirable over a range of scales in order to test existing assumptions fully. Currently, our group is undertaking ^{13}CO measurements of several giant molecular clouds in the hope of shedding light on this longstanding issue.

Observations of higher rotational transitions of CO (e.g., 2→1 and 3→2) are also of interest. Are these largely degenerate with the 1→0 transition, or are they a significant new source of information about physical conditions within molecular clouds? We are now collaborating with several observatories (e.g., Bell Labs, University of Cologne) conducting millimeter and submillimeter observations relevant to such an investigation.

c) High Latitude Studies

Aside from a few surveys that extend to intermediate Galactic latitudes in the direction of previously known star-forming regions, such as the Taurus and Ophiucus dark clouds, only very limited CO observations have been conducted away from the plane of the Galaxy. The IRAS satellite has detected extensive "cirrus" emission at 100 μm (Fig. 2) which suggests the existence of a fairly large amount of molecular gas at high latitudes (Désert et al. 1988). Recent work by our group which indicates that the total amount of molecular gas at high latitudes may be seriously underestimated (Heithausen and Thaddeus 1990, see Fig. 3) emphasizes the need for large, unbiased CO surveys comparable in extent to surveys of molecular clouds near the Galactic plane.
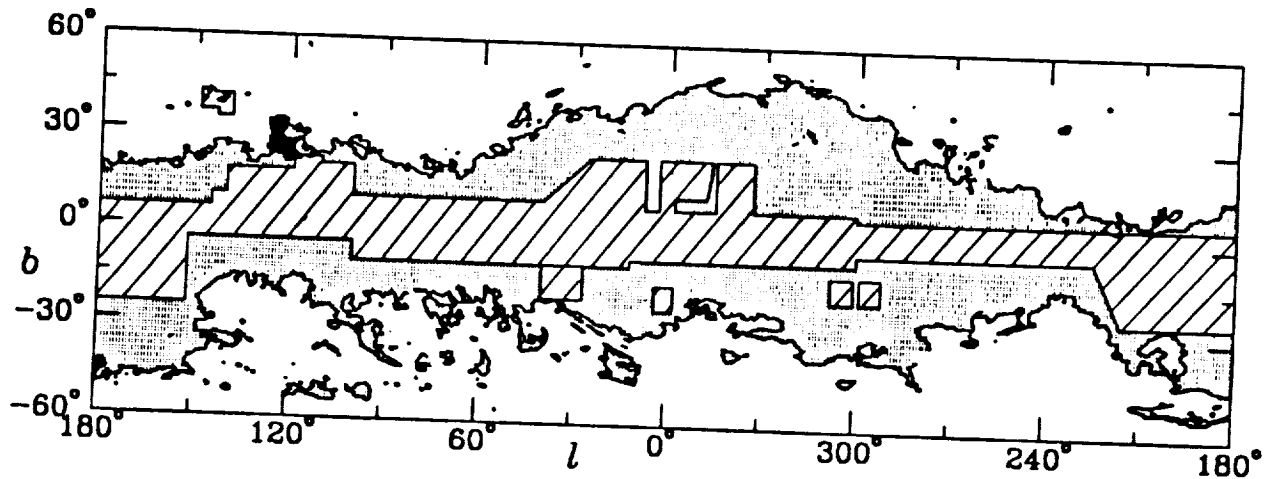
FIGURE 2. Area of most intense IRAS 100 μm emission (above 7 MJy sr^{-1}, in gray) compared with the regions surveyed in CO in the Galactic plane by Dame *et al.* 1987 (dashed area), adapted from Heithausen and Thaddeus 1990.

The CfA millimeter-wave group has undertaken several high-latitude surveys, primarily in the second quadrant of the Galaxy in the vicinity of the north celestial pole (Fig. 4), including (see Tables 1 and 3) investigations of the Cepheus and Polaris Flares and the Ursa Major and similar diffuse clouds possibly related to radio continuum Loop III in this direction ($l,b \sim 135°,35°$). Of particular note for this symposium is a project to map selected regions at high latitude for comparison with high-energy γ-ray observations to be conducted by the EGRET experiment aboard the Gamma Ray Observatory (GRO). Five 10° × 10° fields extending from the Galactic plane toward the north Galactic pole, primarily in the direction of local minima in foreground Galactic material, will be mapped in CO at an angular resolution of 0°.5 degrees. This survey represents the largest fully sampled survey of CO emission at high latitude undertaken to date. The data will be used to place stringent quantitative limits on the amount of molecular material in the observed regions that may contribute to the high-energy γ-ray signal detectable by EGRET (Stacy *et al.* 1990; see § IVc below).
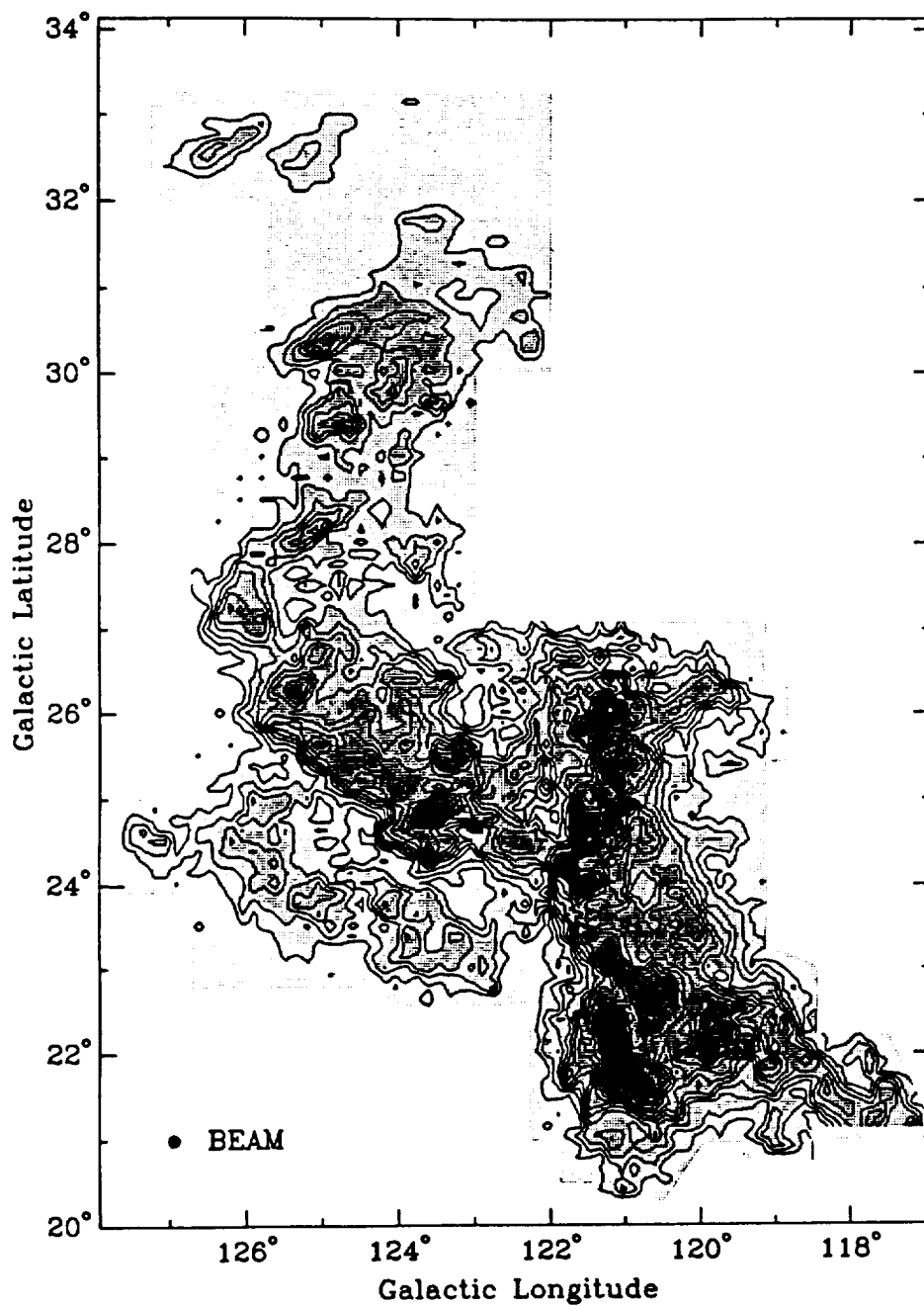
FIGURE 3. Map of velocity-integrated CO emission of the Polaris Flare in the vicinity of the north celestial pole, illustrating the extended and diffuse nature of some high-latitude molecular clouds. Contours range from 0.4 to 13.0 in steps of 0.8 K km s^{-1}, adapted from Heithausen and Thaddeus 1990.

IV. ISSUES RELEVANT TO GRO/EGRET INVESTIGATION

Several areas are outlined below where high-energy γ-ray observations by the EGRET experiment aboard GRO will complement observations at radio wavelengths and may contribute to the resolution of longstanding issues in the study of the structure and content of the Galaxy.

a) Galactic Structure

The strong correlation within the Galactic disk of diffuse, high-energy γ-ray emission and the large-scale distribution of interstellar matter revealed in radio surveys of the Galaxy is now firmly established, based on analyses of data obtained with both the U.S. SAS-2 and the European COS-B satellites (Hartman et al. 1979; Strong et al. 1988). Because diffuse Galactic γ-rays result from cosmic ray interactions with matter, photons, and magnetic fields in interstellar space, models of the diffuse Galactic γ-ray emission can provide insight into the Galactic cosmic-ray distribution and the overall energy balance of the Galaxy and how this equilibrium is achieved by a partition between cosmic-ray and magnetic-field energy densities and gravitational forces due to Galactic matter (Parker 1969). In anticipation of new, more sensitive γ-ray observations by the EGRET experiment aboard GRO, we are participating in an effort to model the diffuse Galactic γ radiation (Bertsch et al. 1990). A particular incentive for this work is the present availability of well-sampled, large-scale radio surveys of the Galaxy in both H I and CO (Weaver and Williams 1973; Burton 1985; and Kerr et al. 1986; Dame et al. 1987); the continuing analysis of the detailed distribution of molecular clouds in the inner Galaxy, in the first quadrant (Dame et al. 1986; Clemens et al. 1988; Solomon and Rivolo 1989) and the fourth quadrant (Bronfman et al. 1990); and the availability of comprehensive recombination-line (Lockman 1989) and near-infrared (Fazio et al. 1990) surveys which may help in resolving kinematic distance ambiguities for a large fraction of the clouds in the inner Galaxy. Further constraints on the CO-to-H_2 conversion factor may be a significant byproduct of such a study, with important consequences for mass estimates of the Galaxy. The greatly enhanced sensitivity and resolution of the EGRET γ-ray telescope, compared with previous experiments of its type, offer the prospect of progress on fundamental questions relating to the distribution, composition, spectrum, and origin of the Galactic cosmic-ray population.

b) The Galactic Center

A notable anomaly to the fairly tight correlation between the diffuse Galactic γ-ray emission and the distribution of interstellar matter is toward the region of the Galactic center ($R \leq 1.5$ kpc), where the γ-ray flux is deficient by nearly an order of magnitude (Blitz et al. 1985). A reexamination of this issue, using a more fully-sampled, wide-latitude CO survey of the Galactic center region (Bitran 1987) and the final COS-B database (Mayer-Hasselwander 1985), attributes the discrepancy between observed and predicted γ-ray emission toward the Galactic center, determined on the basis of mass estimates using the standard $N(H_2)/W_{CO}$ ratio, to a unique population of wide-line molecular clouds. Observations of greatly improved sensitivity and resolution made with the Gamma Ray Observatory should be capable of confirming the wide-line cloud origin of the Galactic center γ-ray deficit and may address important issues related to the origin, evolution, and lifetime of these unique objects and, by extension, of the entire region of the Galactic center (Stacy et al. 1987, 1989).

c) High Latitude and Extragalactic Studies

The γ-ray analyses in the Galactic plane will be extended to intermediate and high Galactic latitudes to isolate the portion of the high-latitude emission believed of extragalactic origin (Fichtel et al. 1978). One challenging problem facing γ-ray astrophysics is the accurate decomposition of the diffuse, high-energy γ-ray emission ($E_\gamma \geq 30$ MeV) into its two fundamental components: the "local," diffuse emission due primarily to nuclear collisions in interstellar space in our own Galaxy and the cosmic, diffuse γ-ray background radiation. The increased sensitivity and resolution of the high-energy EGRET telescope aboard GRO offer the

exciting prospect of decomposition of the diffuse, γ-ray background into its Galactic and extragalactic components. The high-latitude CO observing program described in § IIIc (see Fig. 4), which is of sufficient sensitivity to account for the presence of all molecular gas likely to contribute to a γ-ray signal detectable by EGRET, will be important to this effort, providing crucial information not now available on the distribution and column density of interstellar molecular hydrogen at high Galactic latitudes.
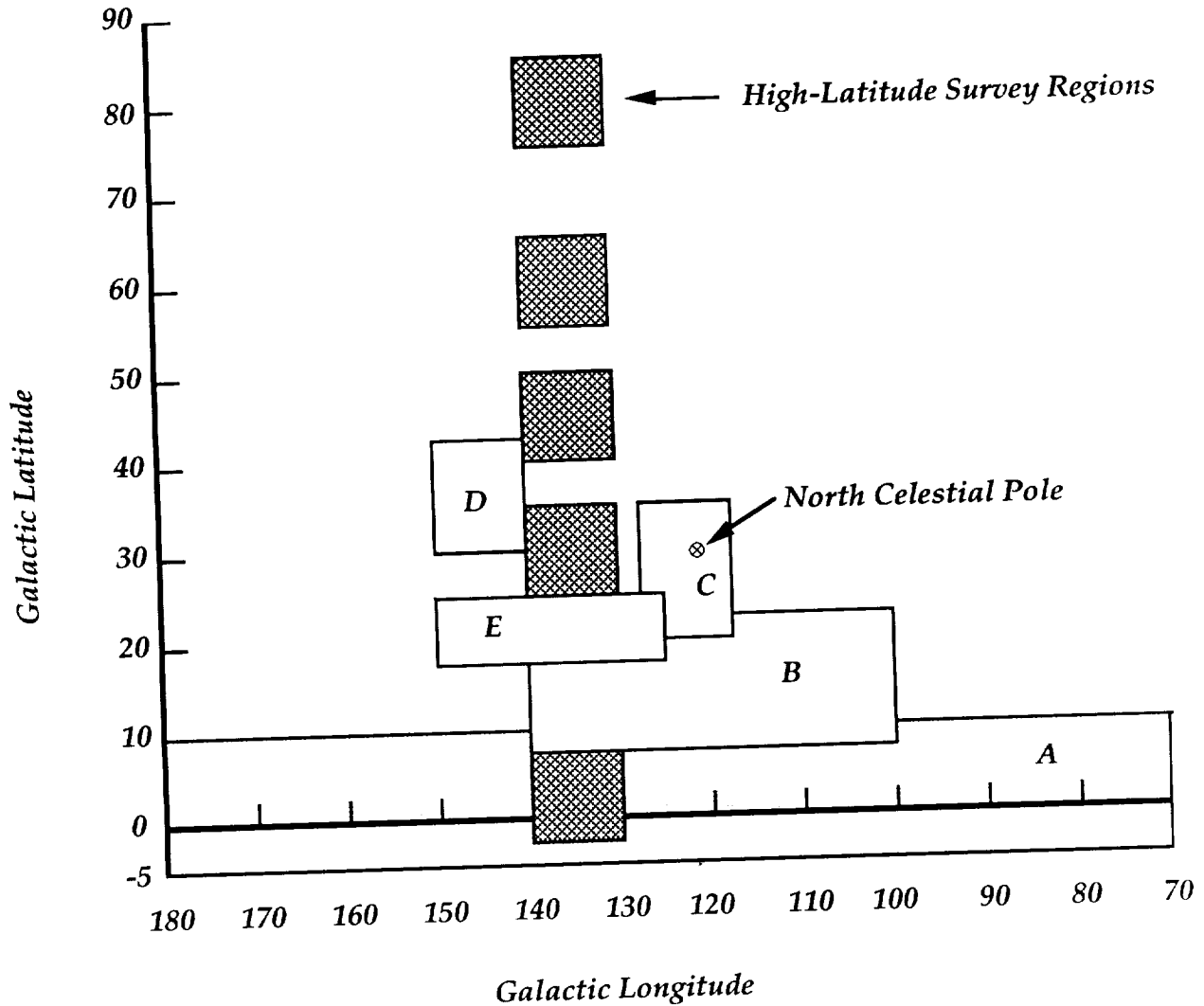

FIGURE 4. Schematic of high-latitude CO survey regions (dark-shaded squares) intended for comparison with GRO observations and their relation to areas previously observed in the second quadrant of the Galaxy with the CfA 1.2 m radio telescope. *Region A:* Part of the CO survey of the Galactic plane by Dame *et al.* 1987. *Region B:* Survey by Grenier *et al.* 1989. *Region C:* Survey by Heithausen and Thaddeus 1990. *Region D:* Survey by de Vries *et al.* 1987. *Region E:* Survey in progress by Heithausen 1990. The position of the north celestial pole is indicated by a ⊗ symbol.

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Finally, the possibility of detecting γ-ray emission with the EGRET telescope from galaxies in the Local Group, in particular the Magellanic Clouds and M31 (Özel and Fichtel 1988), is now quite realistic. Comparison of γ-ray observations with atomic and molecular surveys of these objects (e.g., Cram *et al.* 1980; Brinks and Shane 1984; Rohlfs *et al.* 1984; Cohen *et al.* 1988) will afford a direct measure of cosmic-ray densities in galaxies beyond the Milky Way and may provide an important independent determination of the CO-to-H_2 conversion factor in galaxies with markedly different distributions of interstellar gas.

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DISCUSSION

Gottfried Kanbach:

What is your opinion on the problem of optical depth of ^{12}CO in clouds and on the ratio of $^{12}CO/^{13}CO$ intensity?

Pat Thaddeus:

The optical depth of ^{12}CO in the giant clouds is undoubtedly substantial, since the integrated line intensity ratio W_{12}/W_{13} is approximately 5, while the isotopic ratio is probably not greatly different from the terrestrial ratio 89. It is the remarkable empirical constancy of this ratio when averaged over significant parts of molecular clouds which allows W_{12} to serve as a mass tracer. Just why this should be so in terms of radiation transfer is another matter -- it is not well understood. The constancy of W_{12}/W_{13} is plausibly a result of the very complex fractal structure of the clouds -- an indication that they contain many small unresolved elements which do not occult one another greatly along the line of sight or in radial velocity.

Hermann Rothermal:

Is there any knowledge about magnetic fields in molecular clouds since this will have implications on the gamma-ray calibration of the CO/H_2 empirical factor.

Pat Thaddeus:

This is one of the most serious gaps in our knowledge of molecular clouds, and the prospect of filling it is not good. The Zeeman effect of CO and other diamagnetic molecules is far too small to measure, and the molecules with large moments (e.g., radicals like OH, SO, and CN) do not have very strong lines in molecular clouds. Heiler and collaborators have made heroic efforts to make Zeeman measurements with HI in dense regions, with some success, but at only a few locations. The magnitude and direction of the general field in giant clouds is almost entirely unknown. Many clouds though have a pronounced filamentary structure which one suspects is magnetic in origin.